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SAND AND SAND-KAOLINE MIXTURES CYCLIC PROPERTIES UNDER LOW CONFINING STRESS

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Abstract

The dynamic behaviour of sand and sand mixtures containing low-plasticity fines at low confining stresses is of crucial importance for geotechnical engineering, especially in regions prone to seismic activity. Such materials can be found as natural or man-made deposits or produced in the laboratory. For these mixtures, the accurate assessment and representation of the initial void ratio, defined by the phase relationship or intergranular void ratio, is essential for understanding their cyclic behaviour. The initial void ratio has a direct influence on the response of sand-fines aggregate mixtures under cyclic loading, especially when fines aggregate fills the voids between the sand grains.

Although the cyclic shear threshold for pore water pressure tends to increase with higher plasticity indices, the behaviour of sand mixtures with low plasticity fines remains highly susceptible to liquefaction at low confining stresses. These mixtures exhibit a rapid build-up of pore water pressure and undergo faster cyclic degradation under seismic loads. The problem becomes particularly apparent when the void ratio is calculated using standard phase relationships, which may not fully capture the complex interactions between sand and fines.

This paper presents preliminary findings on the role of fines in filling the voids between sand grains and investigates the behaviour of sand-kaolinite mixtures under dynamic conditions. A series of cyclic triaxial tests were conducted under undrained conditions using both strain and stress-controlled approaches as well as resonant column tests. The results highlight the critical role of intergranular void ratio and effective confining stress in determining the susceptibility to liquefaction and overall cyclic behaviour of sand and sand-kaolinite mixtures under low confining stresses. These results provide important insights into the factors influencing soil stability in seismic environments and emphasise the need for further research on the interaction of sand and low-plasticity fines.

Keywords: stiffness degradation, pore water pressure build-up, sand-kaolinite mixtures, cyclic triaxial test, resonant column test, low confining stress

1. Introduction

The cyclic behaviour of sand mixtures with fines, particularly those containing silt and clay, has attracted significant attention in geotechnical engineering. This interest arises from the need to predict their performance under dynamic conditions such as earthquakes and other vibration induced loading. Research conducted by Thevanayagam [1], Lade et al. [2] and Seed [3], established the influence of fines content and confining stress on the monotonic and cyclic soil behaviour. Recent works, including Othman et al. [4], Akhila et al. [5–7] and Swamy et al. [7], have made some advancement in the understanding of such behaviour, focusing on sand-kaolinite mixtures.

Initial studies on sand-fines mixtures emphasised understanding of their monotonic behaviour, exploring how fines content affects strength and compressibility properties. Later research extended this work to investigate the materials' cyclic loading response, revealing the significant role of fines and how they are influencing liquefaction resistance and cyclic strength degradation. For example, the

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research by Othman et al. [4] highlighted the complex interaction between kaolinite clay and sand particles, and how this interaction can profoundly influence the overall mechanical properties of the mixed material.

Clay minerals introduce complexities in interparticle contacts. Benessalah et al. [8] demonstrated how low-plasticity fines significantly impact instability stress while Nougar et al. [9] and Dafalla et al. [10] found that increasing fines content reduces dilatancy and strength. Wu et al. [11] emphasized the role of fines to creep and secondary compression in sand-clay mixtures.

Fines content and confining stress strongly influence cyclic properties. Studies reveal a non-linear relationship where cyclic strength decreases until fines reach approximately 20%, beyond which it increases [12]. Hyodo et al. [13] noted that strength increases at approximately 30% fines, while Fei & Xu [14] observed fading effects of coarse particles under high cyclic loads. Karim & Alam [15], found that pore pressure generation stabilizes at higher fines content (approximately 35%).

Low confining stresses intensify cyclic strength degradation, particularly in soils with high fines content. Noorzad & Shakeri [16] reported a decrease in post-cyclic monotonic strength at higher fines levels, while Shan et al. [17] described transitional failure behaviours in sand-clay mixtures. For sands with 15–30% fines, cyclic loading significantly alters ultimate strength, with negligible effects in cleaner sands.

Void ratio is critical for predicting soil behaviour, whether the soil is under undrained or drained conditions and whether the soil is loaded monotonically or cyclically. Research has shown that the silty sands' void ratios differ from the void ratios determined for sands using standardized testing procedures and conventional phase relations [1,2,18]. Existing analytical models provided by Chang et al. [19] have been used to redefine the tested silty sands' minimum and maximum void ratios for specimen reconstitution at a targeted relative density. The paper presents the preliminary finding on the role of fines in sand-kaolinite mixtures below fines threshold at low confining stress. Series of cyclic tests were performed on three different material types under the same relative density, based on the redefined void ratios. Focus of the presented results are on the degradation of stiffness and pore water pressure rise.

2. Methodology of performed research

2.1. Materials used

Uniform sand (SK0) and sand-kaolinite mixtures with 10% (SK10) and 15% (SK15) kaolinite content were prepared to examine their cyclic behaviour under low confining stress. Tests were conducted at confining stresses of 25 kPa and 50 kPa, representative of conditions in many geotechnical applications. The sand used was a clean, uniform material with a specific gravity of 2.7. The kaolinite, a commercially available product with a specific gravity of 2.6, was mixed in dried condition with the sand to ensure homogeneity prior to preparing specimens for dynamic properties testing.

Key properties, such as particle size distribution and Atterberg limits, were determined following standardized procedures. Sieve analysis was conducted following European standard [20]. As mentioned, void ratios e_{min} and e_{max} were obtained with existing analytical methods for binary soil mixtures provided by Chang et al. [19]. Liquid and plastic limits were easily obtained for kaolinite, following the procedure according to European standards [21]. For the samples made of sand-kaolinite mixture, the fall cone procedure [22] was used due to the difficulties on the consistency limit determination. The complexity behind the determination of consistency limits for such mixtures are presented in the work done by Marušić and Jagodnik [23]. Physical properties of the material used in laboratory testing are summarized in Table 1.

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Table 1. Physical properties of materials used in research, [24–26]

Physical property	SK0	SK10	SK15	SK100
Specific gravity, G_s (-)	2.7	2.69	2.67	2.6
Eff. Particle size, D_{10} (mm)	0.183	0.054	0.0045	0.00258
Minimum void ratio, e_{min} (-)	0.641	0.473	0.390	0.850
Maximum void ratio, e_{max} (-)	0.911	0.716	0.619	1.640
Plastic limit, w_{PL} (%)	N/A	5.8	9.6	21.6
Liquid limit, w_{LL} (%)	N/A	17.9	17.9	48.3

N/A- non applicable

2.2. Testing equipment

Dynamic properties of artificially sand-kaolinite mixtures were determined using two types of advanced testing systems: (i) Resonant Column device and (ii) Cyclic triaxial device. The two types of system were used due to their possibility to control confining stress and to ensure the full saturation of samples. This ensured the accurate measurement of pore water pressure.

2.2.1. Resonant column device

Resonant column testing is a widely used laboratory method to determine the dynamic properties of soil samples, specifically the shear modulus and damping ratio [27,28]. It involves vibrating a cylindrical soil specimen at different frequencies until resonance is achieved. By measuring the resonant frequency and the rate of decay of vibrations, the shear modulus and damping ratio can be calculated [29,30]. These parameters are crucial for understanding how soil behaves under dynamic loading, such as earthquakes or machine vibrations [31,32].

Recently, the use of the chirp method in resonant column testing has been reported in the literature, e.g. [33–36]. In this approach, the specimen is excited with a frequency sweep rather than a single frequency. This allows for a more comprehensive assessment of the sample's non-linear dynamic response across a broad range of strain amplitudes, providing valuable insights into the soil's behaviour under large deformation conditions.

2.2.2. Cyclic triaxial device

Cyclic triaxial testing was carried out in accordance with ASTM standard [37,38]. Cylindrical specimens, prepared at the same relative densities as the resonant column tests, were subjected to sinusoidal axial loading under constant confining stresses of 25 kPa and 50 kPa. Pore pressure measurements allowed for the evaluation of excess pore pressure ratios r_u during cycling. The cyclic triaxial system's capabilities and calibration details are described in work done by Jagodnik et al. [24,39–41]. Membrane corrections were applied following established methods Duncan & Seed [42] and Lade [43].

2.3. Sample preparation

Samples were prepared using the moist compaction method [44], to ensure uniform density and an even distribution of the soil constituents, thereby preventing fines segregation. The specimens were compacted in ten uniform layers within a latex membrane at the undercompaction of 5%. The initial parameters, including water content, relative density, and void ratio, are detailed in Table 2.

Table 2. Initial parameters of tested materials

Initial parameters	SK0	SK10	SK15
Initial water content, w_i (%)	2	5.8	9.6
Saturated water content, w_{max} (%)	20.5	16.2	14
Relative density, D_r (%)	80	80	80
Initial void ratio, e_0 (-)	0.692	0.681	0.738

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2.4. Test procedures

Specimen prepared using undercompaction method mentioned above were subjected to resonant column tests to characterize the dynamic properties. The testing protocol involved exciting the soil specimen with a frequency sweep and measuring the amplitude, phase response, and torsional shear. Samples were saturated and consolidated to confining stresses of 25 and 50 kPa. After consolidation the samples were loaded with torsional strain amplitude, defined with Table 3. The shear modulus and damping ratio were then calculated from the resonant frequency and rate of decay of the vibrations. Tests were performed in undrained conditions.

Table 3. Initial parameters of tested materials

Test system type	Loading type	Loading values
Resonant column	Torsional shear amplitude [Vol]	0.001, 0.002, 0.005, 0.01, 0.02, 0.05, 0.075, 0.1
Dynamic triaxial test	Cyclic axial strain [%]	0.005, 0.0067, 0.013, 0.033, 0.05, 0.067, 0.13

For cyclic triaxial testing, soil specimens were prepared in the same manner as the resonant column tests. The cylindrical samples were then mounted in the triaxial cell and subjected to sinusoidal axial cyclic strain under constant confining pressures of 25 kPa and 50 kPa, after saturation and consolidation.

3. Results and discussion

This paper presents experimental results of resonant column and cyclic triaxial tests performed to investigate the cyclic shear behavior of soils under low confining stresses. The study focuses on the variation of stiffness degradation, shear modulus and viscous damping as functions of cyclic shear strain, with comparisons to reference trends for soils with different plasticity indices. The results illustrate the dynamic response of soils with low plasticity under different strain amplitudes and confining pressures and provide insights into their stiffness degradation and damping properties.

The Figure 1 illustrates the variation of stiffness degradation via normalized shear modulus $G_s/G_{s,max}$ and equivalent viscous damping ratio λ as functions of cyclic shear strain γ, derived from experimental results of Resonant Column (RC) and Torsional Shear (TS). Tests were conducted at effective confining stresses of 25 kPa and 50 kPa. The experimental data are compared against reference trends for soils with plasticity indices of 0 and 15. For $G_s/G_{s,max}$ the experimental results predominantly follow the trend of the reference curve, especially in the low-to-moderate strain range (0.001%≤γ≤0.01%). At these strain levels, the degradation of shear modulus is minimal, with normalized values remaining above 0.6. This alignment with PI=0 suggests that the tested soil exhibits behavior consistent with non-plastic or low-plasticity materials under cyclic loading.

At higher strains (γ>0.01%), slight deviations from the PI=0 curve are observed, with some data points exhibiting faster degradation of $G_s/G_{s,max}$ These deviations could be attributed to differences in soil fabric, sample preparation methods, or the specific test conditions (e.g., confining pressure and loading history). Nonetheless, the overall trends remain reasonably consistent with the PI=0 reference, indicating that the plasticity of the tested soil is negligible.

For the equivalent viscous damping ratio λ, the experimental results also follow the expected upward trend observed in the PI=0 reference curve. At low strains (γ<0.01%), damping remains relatively low, consistent with typical behavior of low-plasticity soils. As strain increases, the damping ratio exhibits a progressive increase, aligning closely with the reference curve for PI=0.

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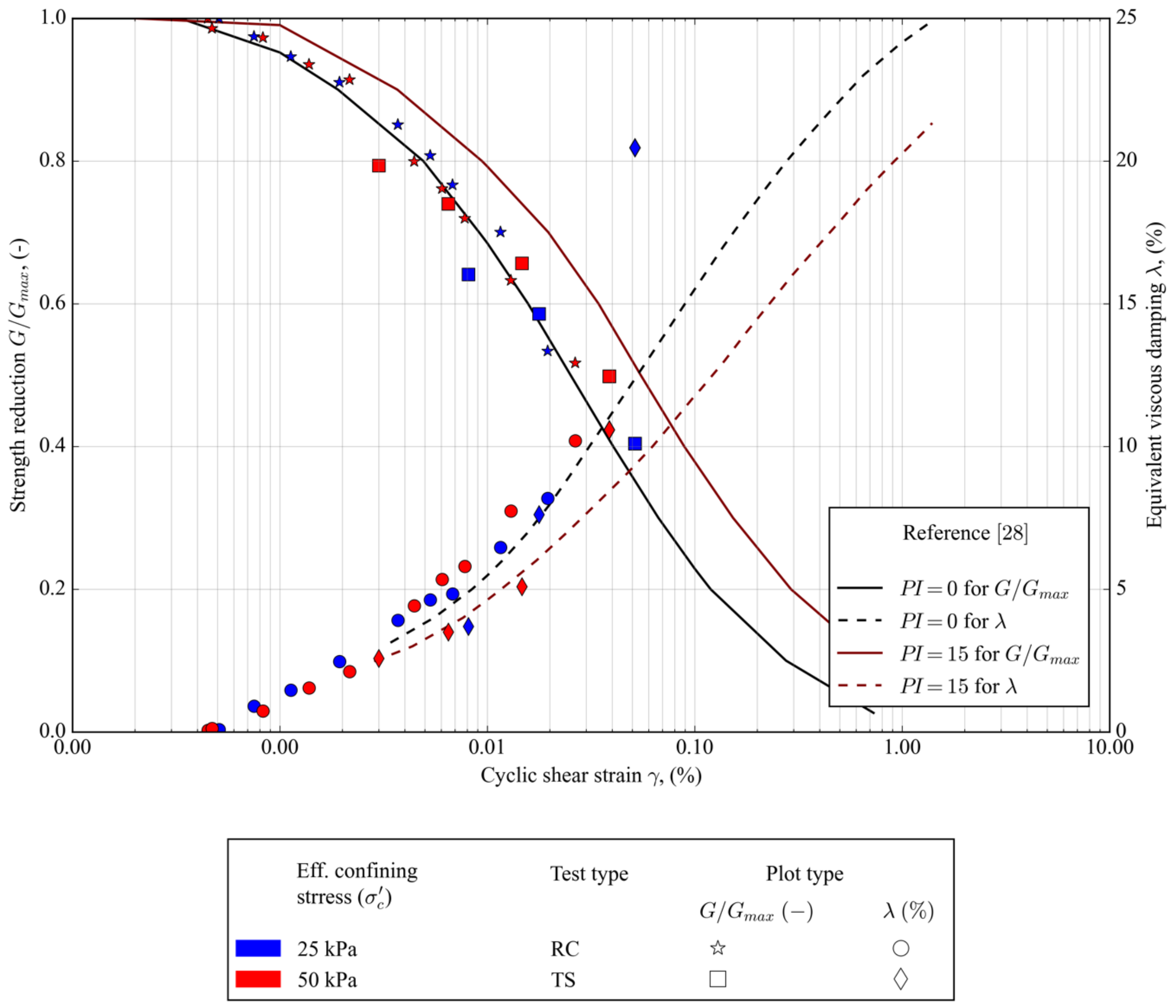

Figure 1. Strength reduction of SK15 mixtures along with equivalent viscous damping

The agreement between experimental data and the PI=0 curve supports the classification of the tested soil as a low-plasticity material. This is consistent with the known characteristics of soils with low or negligible fines content, where plasticity plays a minimal role in dynamic response.

The Figure 2 shows the relationship between normalized pore water pressure (r_u) and stiffness degradation (δ) for cyclic shear strain amplitudes of 0.01%, 0.05%, and 0.1% under effective confining stresses of 25 kPa and 50 kPa. Each subplot corresponds to a specific shear strain amplitude and highlights the progression of stiffness degradation as r_u increases. At low r_u values, stiffness degradation remains minimal, with δ close to 1.0, indicating negligible loss in stiffness, Figure 2a. As r_u approaches 0.65, marked by a dashed vertical line, the stiffness degradation becomes more pronounced, Figure 2b, with greater reductions observed at higher cyclic shear strain amplitudes, Figure 2c. The data also reveal consistent trends across different effective confining stresses, with degradation intensifying at larger strain levels and nonlinear behaviour of material at low cyclic shear strain (Figure 2b and c).

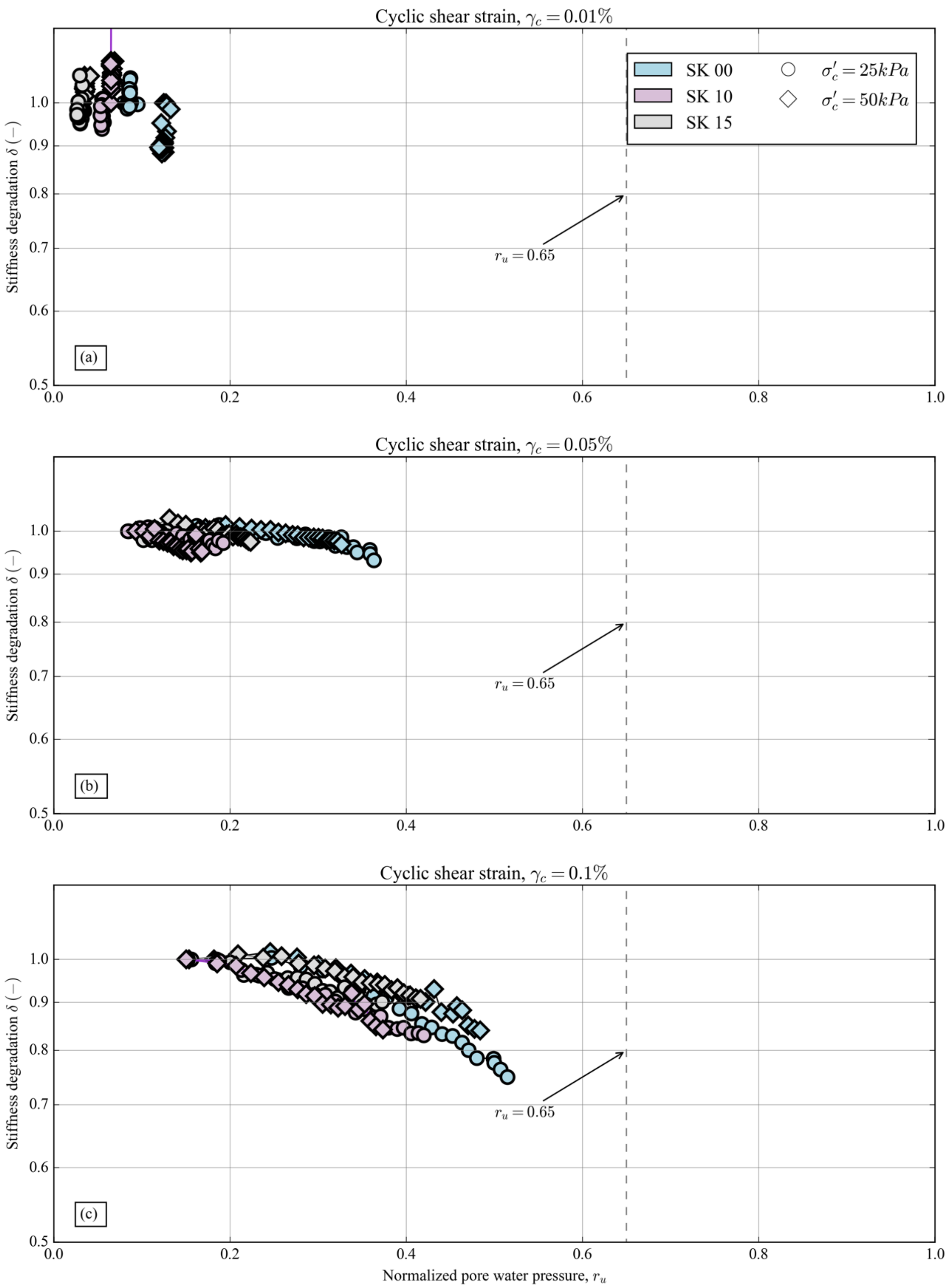

Figure 2. Relation of stiffness degradation and normalized pore water pressure: (a) Cyclic shear strain γ_c = 0.01 %, (b) Cyclic shear strain γ_c = 0.05 % and (c) Cyclic shear strain γ_c = 0.1 %,

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4. Conclusions

This study investigates the dynamic properties of sand-kaolinite mixtures using a comprehensive laboratory test programme that includes resonant column and cyclic triaxial tests. Several important results can be derived:

- Increasing the fines content leads to a reduction in shear modulus at small strains, probably due to the softer nature of the clay fraction.
- Higher fines contents lead to a greater accumulation of excess pore pressure during cyclic loading, indicating an increased susceptibility to liquefaction, especially at lower confining pressures.
- With increasing fineness, the sand-kaolin mixtures experience a greater reduction in stiffness during cyclic loading, as can be seen from the normalised curves for shear modulus degradation.
- Higher limiting stresses lead to higher shear modulus values, lower pore pressure accumulation and less pronounced stiffness degradation.

In summary, it can be said that the dynamic behavior of sand-kaolinite mixtures is significantly influenced by the fines content and the confining stress. A higher fines content reduces the shear modulus at small strains, increases the susceptibility to pore pressure accumulation and accelerates the stiffness degradation under cyclic loading. Conversely, higher limiting stresses improve the shear modulus, reduce the build-up of pore pressure and reduce the reduction in stiffness

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